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Queue-MAC: A queue-length aware hybrid CSMA/TDMA MAC protocol for providing dynamic adaptation to traffic and duty-cycle variation in wireless sensor networks

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Abstract

Existing low-power MAC protocols only provide low throughput because of the fixed low duty-cycle. This often leads to poor performance when dealing with time-constrained burst traffic. In this paper, we propose a new hybrid CSMA/TDMA MAC protocol, called Queue-MAC, that dynamically adapts the duty-cycle according to the current network traffic. The queue length of nodes is used as the network traffic indicator. When the traffic increases, the active CSMA period is accordingly extended by adding dynamic TDMA slots, allowing thus to efficiently handle burst traffic under real-time constraints. This protocol is implemented on the STM32W108 SOC chips and compared with both a fixed duty-cycle reference protocol and an optimized IEEE802.15.4 MAC protocol. Through extensive experimental measurements, we showed that our queue-length aware hybrid CSMA/TDMA MAC protocol largely outperforms the compared protocols. The proposed protocol can be easily implemented through slight adaptation of the IEEE802.15.4 standard. It presents an optimal bandwidth and energy allocation scheme according to the traffic to be carried. In fact, low-duty cycle, so low power consumption is preserved during light traffic load period, while high throughput is obtained during heavy burst load period.

1. Introduction

For saving energy in WSN (Wireless Sensor Networks), the most efficient way is to put the node's transceiver into sleeping mode (radio off). A node is thus periodically either in active state or in inactive (sleeping) state. The duty-cycle is defined as the proportion of the active period over the total period (active + inactive). It is obvious that a WSN operating with low duty-cycle

results in lower energy consumption. This has led to the development of numerous low duty-cycle MAC protocols [1][2].

The low duty-cycle mode is suitable for reporting rarely occurred individual event since low network throughput is generally sufficient. However because of the low throughput, it is not efficient for handling burst events, which may generate, during a short period, important traffic to be timely carried by the network. Let's take the example of the IEEE 802.15.4 standard data rate of 250 Kbps, when operating in a low duty-cycle mode fixed to 1%, the total enabled throughput is only 2.5 Kbps.

Burst traffic does exist in many application scenarios. For instance, by only citing one among many others, in a building automation or more generally environmental monitoring application, wireless sensors may be deployed for detecting and real-time tracking of intruders entering to the monitored area. When no intruder is detected, the network can be satisfied to operate in a very low duty-cycle mode. When one or more intruders are detected (often simultaneously detected by several neighboring sensor nodes due to their dense deployment), the event must be quickly reported to the sink node. Moreover, when real-time target tracking is supported, those events will also trigger additional burst traffic related to the target tracking.

Instead of using a fixed duty-cycle MAC protocol, the previous example motivated us to look for a MAC protocol, which can dynamically adjust its duty-cycle according to the amount of traffic that the network should carry. From our understanding, saving energy is of course one of the most important issues in WSN. But when urgent events occur, a WSN must also be able to report them whatever the energy cost. For instance, it is no longer necessary to preserve energy for a forest wildfire monitoring WSN when a fire point is detected. The energy conservation is only meaningful before the fire occurs. So from our point of view, in contrast with some common understanding, energy saving and network QoS (quality of service) are not two antagonistic issues for most of the applications, but each

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issue has its own period. Again this calls for developing dynamic duty-cycle protocols.

Either CSMA or TDMA scheme is used in the active period for the medium access control of nodes. It is well known that, 30 years ago [3], CSMA exhibits better performance under light traffic load whilst TDMA has better performance under heavy traffic load. When used in WSN, CSMA is flexible and simple, and it guarantees quick medium access in light traffic. While in heavy traffic, CSMA suffers from collisions, leading to performance degradation. TDMA, due to its collision free medium access scheme, is more efficient under heavy traffic load, but it has poor scalability. Moreover maintaining TDMA schedule may lead to huge overhearing and so energy wasting. So in addition to looking for a dynamic duty-cycle scheme, it is also interesting to smartly combine the advantages of both CSMA and TDMA during the active period for obtaining high packet transmission performance.

In the literature, numerous interesting low power MAC protocols have been developed. IEEE 802.15.4 MAC [4] and Z-MAC [5] are protocols that adopt both CSMA and TDMA schemes. B-MAC [6], WiseMAC [7], X-MAC [8], and TrawMac [9] are all CSMA-based ones. Most of them adopt low power listening (LPL) technique, and can also offer certain flexibility in adapting their duty-cycle according to the traffic loads. We will go into details of these MAC protocols as related works in Section 2. They present separately either hybrid CSMA/TDMA or dynamic duty-cycle, but these two issues are not combined.

In this paper, we propose a new hybrid CSMA/TDMA MAC protocol, called Queue-MAC (queue-length aware MAC), to solve the two above-mentioned problems, namely “fixed duty-cycle problem” and “CSMA and TDMA shortcoming problem”. The idea is combining the strength of CSMA and TDMA while offsetting their weakness. The new MAC protocol contains a fixed length CSMA period and a dynamic TDMA period in its superframe structure. A queue indicator is defined in MAC packet structure to show the load of node. Based on the reception of the queue indicator, parent node (cluster head or router) allocates additional TDMA slots to its heavily loaded children nodes.

By dynamically allocating TDMA slots, the network adapts in fact its duty-cycle (or bandwidth) according to the traffic load, and achieves short packet delay and high channel utilization in all scenarios (i.e. both light traffic and burst traffic). The hybrid MAC maintains high scalability due to its CSMA period. Except beacon frame and ACK frame, no other control packet is needed; so all nodes get medium resource implicitly. The hybrid MAC also achieves high energy efficiency since energy is only used when there is traffic to handle.

The rest of the paper is organized as following. In Section 2, we further review some existing work related to the two above-mentioned problems. Section 3

describes our hybrid CSMA/TDMA MAC protocol and Section 4 analyzes its advantages. Section 5 presents our implementation on the STM32W108 SOC chips [10] and the performance evaluation by comparing it with both a fixed duty-cycle reference MAC and the existing IEEE 802.15.4 MAC standard. Concluding remarks are given in Section 6.

2. Related Works

IEEE 802.15.4 standard is designed for low data-rate network and it adopts duty-cycle scheme in beacon enabled mode. Time axis is divided into superframes, which has a fixed duty period. A superframe is composed of active period and inactive period. Active period contains 16 equally spaced slots which are further classified into Beacon Period, Contention Access Period (CAP) and optional Contention Free Period (CFP) also known as Guaranteed Time slots (GTS). In Contention Access Period, nodes use slotted CSMA/CA to contend for transmission. For critical data transmission, nodes may apply for contention free GTS slots for guaranteed transmission. But only up to 7 GTS slots can be applied in the standard. IEEE 802.15.4 is CSMA/TDMA hybrid MAC, which reserves scalability and also provides considerable guaranteed transmission. However, active period length in IEEE 802.15.4 MAC must be configured by parameters BO and SO and cannot be on line extended to handle burst traffic load, which lead to limited bandwidth.

Z-MAC is another well-known WSN MAC that adopts both CSMA and TDMA mechanism. In Z-MAC, CSMA is used as the baseline scheme and TDMA is used as a “hint” to enhance contention resolution. The owner of one TDMA slot gets higher priority to access the medium by having shorter contention window. Non-owners can steal the slot when the owner do not have packet to send, this provides good channel utilization. Z-MAC only falls back to CSMA in the worst case. But as Z-MAC still uses fixed TDMA schedule, topology changes and synchronization errors may affect the protocol property.

B-MAC uses CSMA as its main scheme and adopts LPL and preamble technology to conserve energy. Each node has its own schedule, which is composed of waking period and sleep period. Receiver samples the channel and receives the packets. To adapt to the varying traffic load, B-MAC can change its sleep schedule by using an application interface, which is offered by the author. B-MAC achieves high throughput and low latency, but it suffers from the overhearing problem and the extra energy consumption due to long preamble frame.

WiseMAC improved B-MAC by reducing the preamble length. Node records wake-up schedules of its neighbours and starts preamble just before the sampling period of the receiver. An additional bit in the header of the data packets is designed to indicate following packets thus multi packets can be transmitted in one shot. To

reduce preamble length and overhead consumption, X-MAC divides preamble frame into small pieces and each piece is attached with destination address. TrawMAC is a traffic-aware MAC that adopts preamble strobing technique like X-MAC. TrawMAC also provides throughput flexibility by using a special field to indicate queued packets; multi-packets can be forwarded in one transmission attempt. So its traffic adaptation mechanism is similar to that of Queue-MAC.

Although B-MAC, WiseMAC, X-MAC and TrawMAC all provide certain flexibilities in adapting throughput, they all use CSMA as their basic mechanism. When channel competitors are in large number due to heavy burst traffic, many of them may still suffer from high collisions which leading to limited throughput and thus considerable latency.

3. Design of Queue-MAC

In this section, we present a queue-length aware hybrid CSMA/TDMA MAC protocol, Queue-MAC, for multi-hop networks that adopt beacon-enable superframe structure (e.g., ZigBee [11]/IEEE 802.15.4). Parent nodes like routers or cluster heads in the network periodically broadcast beacon frames to divide time into repeating superframes that contain active period and inactive period. Most of tasks and communication activities are arranged within the active period while in the inactive period all children nodes and parent nodes turn off their radio to conserve power.

Our MAC protocol design is motivated by the conflict between limited duty-cycle (or bandwidth) and burst network traffic loads. Without modifying the existing IEEE 802.15.4 MAC header, we add a specific field into the payload field of the IEEE standard MAC packet structure, called “queue indicator” to describe the node’s load. Then we propose a novel superframe structure composed of beacon frame, variable TDMA period, fixed CSMA period and inactive period. The variable TDMA slots are decided by the loads of nodes that can be learned from the piggybacking queue indicators of received packets. When the traffic increases, the active period is accordingly extended by adding more TDMA slots to increase the bandwidth.

3.1. MAC packet structure

In general, packet delay in MAC layer is due to the following factors: (1) buffering delay generated in the packet forwarding queue; (2) forwarding delay; (3) signal propagation delay; (4) receiving and processing delay. Except the first factor, all the later three factors highly depend on the physical hardware conditions, which count a little due to fast speed processor and signal propagation. Therefore, the buffering delay in the forwarding queue makes up the main part of the total packet delay. When a sensor node gets a data packet to send out, it firstly puts the data packet into its forwarding

queue of the MAC layer and then waits for the action of the radio. If the sensor node gets the authority to occupy the medium, it takes the packet out of the queue and sends it out. Otherwise the packet has to be buffered in the queue for its chance to be forwarded. Mostly, the buffering delay is related with the communication resource the node could get. If the node can occupy the medium all the time, normally no packets will be buffered in the forwarding queue unless the network is overload (i.e., the packet arrival rate is higher than the maximum departure rate). On the contrary, if the node shares little part of the communication resource and coming data packets get pushed into the forwarding queue continuously, packets will have to be accumulated in the forwarding queue and wait for long time until the channel is free for the node again.

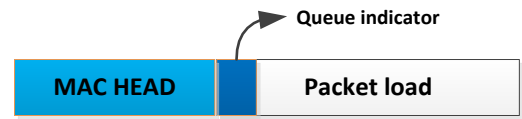


Figure 1. MAC packet structure

In order to balance the chance of accessing the medium among sensor nodes, the load of each sensor node should be learned. Intuitively, the sensor node with heavy load should have greater chance of accessing the medium and sending packets. Therefore, we present a slightly modified MAC packet structure, as shown in Figure 1. In this packet structure, a one-byte queue length indicator is introduced to describe the load of the node. To be consistent with the existing MAC and PHY standards (e.g., IEEE 802.15.4) without modifying it, we define the queue indicator as the first byte of the packet payload. The queue indicator is supposed to have a value equals to the number of the currently buffered packets in the forwarding queue. The node sets the value of the queue indicator of the current sending packet according to the node’s current queue condition. By broadcasting out the data packet along with the indicator into the wireless medium, the node tells every possible receiver about its packet load condition. For instance, once a parent node receives a packet from its children node, the load of the children node will be learned by the parent node from the queue length indicator. Then the parent node can accordingly allocate TDMA slots to the children node in its superframe structure. We will present the designed superframe structure in detail in Section 3.2.

3.2. Traffic transmission control

The designed superframe structure of Queue-MAC is shown in Figure 2. The superframe is composed of four parts: beacon period, variable TDMA period, fixed length CSMA period and inactive period.

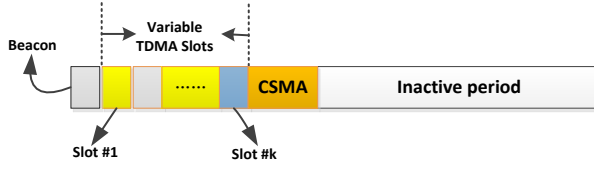


Figure 2. Superframe structure

Compared with conventional CSMA protocol, a variable TDMA period is added into the superframe between the beacon frame and the fixed length CSMA period. The length of the TDMA period (number of time slots) and which node should be allocated with time slots are decided by the queue length indicators of each node received by their parent node. The larger the queue length indicator, the more the packets buffered, therefore, the more time slots the node should be allocated. In this way, nodes with buffered packets will be allocated time slots in the variable TDMA period, which avoid the collision between multiple nodes under heavy traffic.

Most of the traffic will be handled by the variable TDMA method, however, some nodes may not have chance to access the medium any more if we just use the TDMA method because they are not allocated with any time slot in current period and the load of them will never be learned by their parent nodes. In order to solve this problem, a fixed length CSMA period is designed following the variable TDMA period. During this CSMA period, each node has the chance of sending out packets by using CSMA/CA mechanism. Since most of traffic has been handled in the TDMA period, traffic in the CSMA period is normally small, which reduces the probability of collisions and retransmissions. That is the reason why we put TDMA period ahead of CSMA period. After the CSMA period, all nodes turn off their radio to conserve energy during the inactive period. In the following, we will present the implementation of the hybrid CSMA/TDMA Queue-MAC in detail.

Once an event is detected by the sensor nodes, sensor nodes deployed in the related region will start to generate reporting packets intensely, which results in a dramatic increase of traffic loads. If the current bandwidth is insufficient to handle the traffic in short time, packets may start to be buffered in the forwarding queue. In this case, the queue indicator of the sent out data packet is not zero for nodes having several packets buffered in the forwarding queue.

After receiving packets with queue indicators from children nodes, the load of each node will be learned by the parent node which then allocates time slot accordingly in the variable TDMA period. In order to allocate time slots accurately and efficiently, an ID list and a slot allocating list are added into the beacon frame structure which is shown in Figure 3. The ID list maintains the IDs of nodes with allocated time slots. The slot allocating list maintains the number of allocated time slots for each node in the ID list. Once a packet is

received, the ID list and the slot allocating list are updated by parent node.

Header	Slots #	ID list	Slot Allocating list
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Figure 3. Beacon frame structure

Upon receiving one packet from a node, the parent node goes to the ID list to check whether the corresponding node has been allocated TDMA slots before. If not, the parent node then checks the queue length indicator byte of the received packet. If the value of the indicator is zero, which means that the corresponding sensor node has an empty forwarding queue, the parent node puts the packet into its queue and takes no further actions. If the parent node finds the value of the queue length indicator is not zero which means the corresponding node has one or more packets buffered in the forwarding queue, the parent node then adds the ID of the node into the ID list. Based on certain kind of allocation strategy, it finds out how many slots should be assigned to the node in the next superframe. While if parent node finds that the corresponding node has been allocated TDMA slots formerly and its queue indicator is zero this time, the parent node wipes the node's ID out of the ID list. If the queue indicator is non-zero, the parent node reassigns the number of allocated slots to the node based on the current queue length indicator.

The slot allocation strategy is described as following.

Slot Allocation Strategy: Suppose the packet length is fixed, and the duration of one TDMA slot is defined to be just sufficient for one single packet transmission with ACK confirm. The number of allocated slots for every node is proportional to its queue length indicator value. For example, a node sending out packet with queue length indicator indicating 3 buffering packets should be allocated 3 TDMA slots in the next superframe cycle. Suppose there are n nodes which need to be allocated with TDMA slots, the total number of allocated slots C is given by the equation (1):

$$C = \sum_{i=1}^n N_i \quad (1)$$

where N_i denotes the number of allocated slots of node- i . Since the superframe has fixed length, there is an upper bound of the allocated slot number, which is expressed by equation (2):

$$M = \frac{T_S - T_B - T_C - T_R}{T_{\text{slot}}} \quad (2)$$

where T_S denotes the duration of the superframe structure, T_B and T_C denote the beacon duration and the fixed-length CSMA period duration respectively, T_R is the maximum time the parent node needs to retransmit the collected packets to upper level node, and T_{slot} is the

TDMA slot duration. Thus, M is the maximum number of slots that can be allocated. Let K denotes the actual number of allocated time slots, then we have

$$K = \min(C, M) \quad (3)$$

In case where C is bigger than M , parent node will allocate the M slots to n nodes proportionally according to their queue indicator values.

While if packet length is not fixed, the problem will become complicated. The number of allocated slots should be carefully calculated for each node based on different packet lengths. We leave that as our future work.

Comparing to a fixed duty-cycle scheme with only fixed length CSMA active period and inactive period, this dynamic TDMA slot allocation strategy provides obviously better performance (see Section 4 for a qualitative analysis), resulting in higher throughput, lower packet delay and more efficient energy consumption.

In the rest of this paper, for easing the understanding of the performance improvement analysis of the hybrid MAC, we use a simpler allocation strategy described as following.

Simpler Slot Allocation Strategy: A threshold T_1 is set to control the slot allocation. Nodes having packet buffering number greater than the threshold T_1 should then be allocated slots for TDMA transmission in the next superframe. In order to disperse the traffic load as quickly as possible, we set the threshold T_1 to be 1, which means that once the parent node finds the corresponding children node has at least one packet waiting in the queue, the children node will be allocated one TDMA slot for the next superframe transmission and put the children node's ID into the ID list.

For those nodes having queue indicator value greater than a threshold T_2 ($T_2 > T_1$), two TDMA slots will be allocated in the next superframe by the parent node. Here we set T_2 to be 2 in order to better see how the additional slots contribute to the performance improvement (see Section 5). T_1 and T_2 refer to how quick the hybrid MAC can act to the load.

At the beginning of every superframe, parent node broadcasts its beacon frame. Upon reception of the beacon frame, each node first checks whether its ID is inside the ID list. If yes, the node realizes that it has been allocated TDMA slots in this superframe, and then it finds out where and how many slots it has been allocated in the slot allocating list. The node waits for the start of the allocated slots and sends their packets directly without contention. If the node found that it has not been allocated any slot and it has packets in its forwarding queue, it can still try to send them out in the CSMA period using the CSMA/CA mechanism. As the traffic load grows, more nodes may have buffered packets in

their forwarding queue. The parent node learns the current traffic condition by checking the queue length indicators of the received packets and then allocates time slots accordingly in the TDMA period.

On the contrary, the length of the variable TDMA period may decrease or even disappear under light traffic. For instance, when there is no target in the target tracking application, few nodes in the network get packets to report to their parent nodes. Since few nodes get packets buffered in the forwarding queue, few TDMA slots will be allocated. Therefore, the length of the variable TDMA period will be very short. For considering an extreme case under light traffic situation that no node gets packet to send out, so no buffering packet will be found, and thus no TDMA slot will be allocated. In this case, there will be no TDMA period, and the structure of the superframe will be what Figure 4 exhibits. A single short CSMA period is used to handle all the scattered transmissions without heavy collisions.



Figure 4. Superframe structure under extreme light traffic

For beacon-enable multi-hop tree network (e.g., ZigBee network), the node acting as parent node of lower level nodes, may be the children node of upper level nodes, and it forwards its data using the same scheme as described above. Parent nodes and their children nodes adopt superframe structure with a phase offset, similar to the superframe scheduling principle [12] of ZigBee multi-hop tree network [11]. Its detail is out of the scope of this paper. Its performance evaluation is our future work.

4. Protocol property analysis

4.1. Throughput and packet delay

Unlike most duty-cycle MAC protocols that have fixed length of active period which can't find an efficient way to allocate the bandwidth resource, Queue-MAC can dynamically change its duty-cycle according to the load of network and achieve dynamic bandwidth. Fixed length of active period results in fixed bandwidth and can't guarantee real-time communication under heavy traffic. Our proposed hybrid MAC is more flexible in dealing with dynamic traffic loads. When it is under the extreme light traffic scene, there will probably be no TDMA period in the superframe. A CSMA period provides enough bandwidth to handle the scattered packets and guarantees small packet delay like other CSMA protocols. As the traffic load grows, Queue-MAC adapts its bandwidth to the traffic by reasonably and dynamically changing its TDMA slots number. The

MAC will achieve higher throughput due to TDMA slots assignment and thus guarantee smaller delay. In all, based on the traffic loads, Queue-MAC can dynamically decrease or increase the active period to counter the changing load, thus lead to adaptive throughput and small packet delay.

4.2. Scalability

The scalability of the designed protocol is maintained by the CSMA period in the superframe. This period is short but crucial. It guarantees the flexibility of the MAC protocol. Any node that wants to join the network can simply wait for the beacon frame of the parent nodes. By analyzing the beacon frame, it knows when the CSMA period starts and sends packets to the parent node to claim its joining. TDMA slots are only allocated to current active nodes, so when something causes a node failure or leaves, it does not affect the network at all. Therefore, unlike TDMA mechanism that maintains a relatively fixed schedule, Queue-MAC does not limit the slot number and the number of nodes in the network.

4.3. Energy efficiency

Unlike most CSMA mechanisms that suffer great throughput degradation from high contentions, Queue-MAC mitigates traffic loads mostly in the TDMA period, thus alleviates possible contentions and retransmissions in the CSMA period, results in power saving. A node will turn off its radio if it is not in its own slot, or not in the CSMA period, and if it has no data to send. So there will be no overhead for sensor nodes. Unlike TDMA mechanism that has fixed schedule, TDMA slots in Queue-MAC are only allocated to those nodes which have buffered data packets, so no slots will be idly wasted, and only in CSMA period can idle listening occur. But as we have defined a relatively short CSMA period, not much power will be consumed due to idle listening. There are only two kinds of control packets defined in the protocol: beacon packet and ACK packet. Nodes in the network apply for the communication resource implicitly, and no other control packets need to be defined to maintain the function of the protocol. In all, we believe that we have designed an energy efficient MAC protocol.

5. Experimental evaluation

To evaluate the realistic performance of our hybrid MAC protocol, we implemented it on the STM32W108 SOC chips and set up a test bed (see Figure 5) to compare Queue-MAC with two kinds of MAC protocols. First we compared our MAC with a simple fixed duty-cycle CSMA reference MAC protocol to see the effectiveness of Queue-MAC. The duty length of the duty-cycle CSMA reference MAC protocol was fixed, and we varied the duty length to get different bandwidth. In order to validate that our MAC can be implemented in

existing standard, we also compared Queue-MAC with an optimized IEEE.802.15.4 MAC.

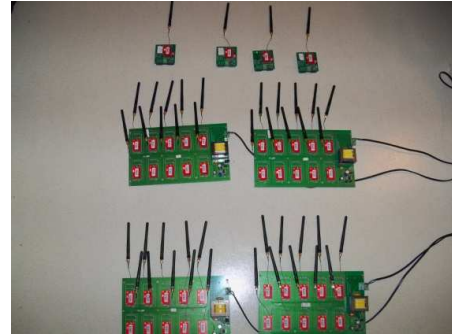


Figure 5. Experiment test bed

5.1. Comparison with fixed duty-cycle CSMA reference MAC protocol

5.1.1. Implementation

We set up a network that has clustering topology, and run both Queue-MAC and the duty-cycle reference MAC on it. The network has a topology as shown in Figure 5. The network is composed of 1 sink node and 4 clusters, each cluster contains up to 10 nodes and 1 cluster head. In this experimental evaluation, we defined a simple duty-cycle CSMA reference protocol with a superframe structure resembles to Figure 4. The duty length of the active CSMA period is fixed, in which nodes use CSMA/CA to send packets, and by varying the duty length, we changed the bandwidth and throughput of the reference protocol.

For both MACs, the superframe has duration of 500ms. Each node was programmed to generate data packets in Poisson distribution with a mean interval of 500ms, and each data packet contains 120 bytes. Each node has a forwarding queue limited to 45 packets maximum. Data packets are generated by nodes and transmitted to cluster heads, and then the cluster heads forward the collected packets to the sink node in the same superframe after the active period. To clear interference between 4 closely deployed clusters, each cluster was programmed to work on different channels during active period, but all cluster heads forwarded their packets to the sink node on the same channel using CSMA/CA.

For Queue-MAC, we set the CSMA period to be 20ms, and defined the TDMA slot to be 5ms to handle one single packet transmission and ACK confirm. The simpler slot allocation strategy was implemented with threshold T_1 to be 1, and T_2 to be 2. For the reference CSMA protocol, we varied the CSMA period to have different lengths: 20ms, 40ms and 80ms.

By increasing the number of nodes attending in the network from 1 to 40, we simulated the growth of the traffic load in 40 different experimental scenarios. Each scenario of the experiment lasted for 40 seconds and was

conducted once. Figure 6 through Figure 10 show the results.

5.1.2. Experimental results and analysis

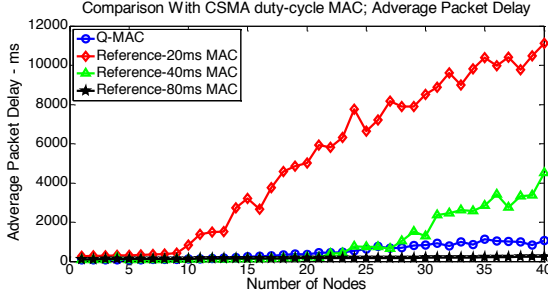


Figure 6. Average packet delay of Queue-MAC and duty-cycle reference MACs

Figure 6 shows the average packet delay of different MACs. The packet delay is measured by the difference between the time the packet was generated and the time it was received by the sink node. We took the mean value of all the successfully received packets. As shown in Figure 6, the reference-80ms MAC has the best performance, while the reference-20ms MAC has the largest delay in all scenarios and can have delay at most 14.7 times (nodes number=14) as Queue-MAC. Before the scale of the networks gets 10, all the MACs have almost the same performance (<500ms, less than one frame cycle). At the scale of 10 nodes, the channel of reference-20ms MAC starts to get saturated, packets cannot be forwarded in time and start to be buffered in the queue, causing increasing delay. Reference-80ms MAC has surpassing bandwidth to forward every generated packet, so the delay nearly stays the same at a very low level (<250ms). Queue-MAC reacts to the increasing loads by adaptively allocating TDMA slots to counter it, the delay just increases slightly.

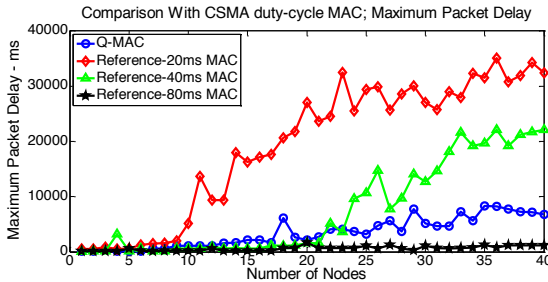


Figure 7. Maximum delay of Queue-MAC and duty-cycle reference MACs

Figure 7 shows the maximum delay the packet could experience during each scenario. As the forwarding queue can buffer at most 45 packets and we set the packet rate to be nearly one packet every 500ms, the packet could at most be buffered in the queue for 22.5 seconds before the queue is overflow. Figure 7 shows

that the maximum delay can be 35.1 seconds in the reference-20ms MAC, which means the specific node has dropped at least 25 $((35.1-22.5)/0.5)$ packets (although the forwarding from cluster head to the sink node takes time, it will be completed in the same frame period within 500ms). No packet is dropped in Queue-MAC due to queue overflow. Figure 7 is complementary to the average packet delay of Figure 6. We can see similar performance from the figure that Queue-MAC has much smaller delay than the reference-20/40ms MAC and behaves slightly worse than the reference-80ms MAC.

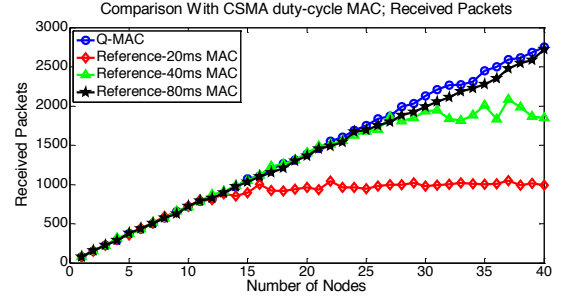


Figure 8. Received packets per scenario of Queue-MAC and duty-cycle reference MACs

Figure 8 shows the number of successfully received packets per scenario of all MACs, and here we simply define the throughput to be the received packet number during one scenario. The throughput of Queue-MAC and the reference-80ms MAC grow linearly as the node number increases. The reference-20/40ms MACs have limited bandwidth while their throughputs turn to be bounded at different network scales. When network scale reaches 40 nodes, around 3000 packets are generated in all. More than 60 percents of generated packets are dropped due to bandwidth limit in reference-20 MAC and those about 40 percents in the reference-40 MAC. Queue-MAC almost hits the point by successfully receiving 2751 packets. Figure 8 also shows that Queue-MAC can adaptively change its bandwidth according to the traffic loads and achieve high throughput.

Figure 9 shows the mean buffered packet number of all nodes at the end of each scenario. It reveals the internal information corresponding to the packet delay and throughput. In the reference-20ms MAC, the buffered number starts to rise after the network scale grows beyond 9 nodes, and reaches 40 at the end. As the maximum queue length is 45, we can infer that most nodes' queues get overflowed when the mean buffered number nearly hits the top. Packets wait for a long time to be sent out and newly coming packets are probably dropped, resulting in huge packet delay and limited throughput. The reference-80ms MAC has surpassing bandwidth to forward all the generating packets immediately, so no packet is buffered in its queue. In

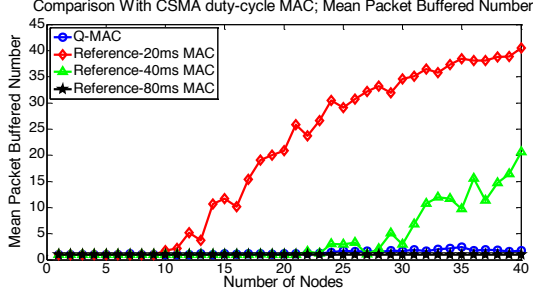


Figure 9. Mean buffered number of Queue-MAC and duty-cycle reference MACs

Queue-MAC, the buffered number grows slightly with the traffic load. This is mainly because Queue-MAC adaptively allocates TDMA slots to mitigate the increasing load. Figure 10 reveals how Queue-MAC compensates traffic loads at a first hand.

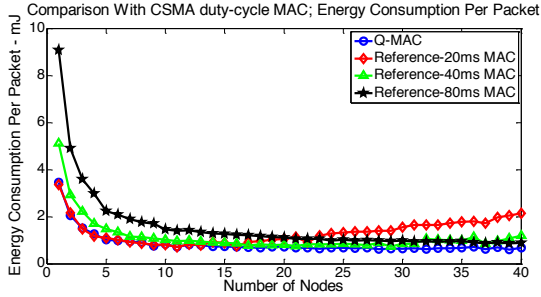


Figure 10. Energy efficiency of Queue-MAC and duty-cycle reference MACs

Figure 10 shows the comparison in energy efficiency. For all MACs, we calculated the effective energy consumption by using equation (4), in which energy consumption per successful packet transmission is divided by packet success rate.

$$\frac{E_{\text{Total}}}{N_{\text{success}}} / \frac{N_{\text{success}}}{N_{\text{Total}}} \quad (4)$$

where E_{Total} is the total energy consumption of cluster heads per experimental scenario, N_{success} denotes the number of successfully received packets, N_{Total} is the number of the totally generated packets. The reason to also consider in equation (4) the packet success rate is that for a given total packet number N_{Total} , each MAC protocol may drop different number of packets, leading thus to different N_{success} . Only using $(E_{\text{Total}}/N_{\text{success}})$ will result in unfair comparison since sometimes, smaller N_{success} with smaller E_{Total} may be wrongly considered better by forgetting that the protocol should also be able to carry N_{Total} packets.

Based on the findings in [13] and the characters of the chip [10] we used, we assumed that power consumption under receiving/idle state and transmitting state are the

same, as 30mA. Thus the effective energy consumption is shown in Figure 10.

At the beginning, when the traffic is extremely light, all MACs consume high power to send one single packet due to idle listening in the initial CSMA period of Queue-MAC and the fixed duty period of duty-cycle MACs. As traffic grows, increasing channel utilization results in less idle listening, the energy efficiency thus increases. To specifically different loads for different MACs, when the channel is just saturated, with the bandwidth equals the load, all MACs hit their optimal points of energy efficiency. That means the bandwidth each MAC provides matches right the bandwidth required by the network to carry out the load. While when the traffic load grows beyond the bandwidth of duty-cycle MACs, packets loss starts to occur because of the queue overflow. Then the decrease of the packet success rate in the divisor of equation (4) contributes to the rising of energy consumption per successful packet. So, we can see that energy consumption per packet of all duty-cycle MACs slightly rises after they hit their optimal points as traffic grows. Queue-MAC keeps its low energy consumption per packet as traffic grows. This is mainly because that the adaptive TDMA slots allocation of Queue-MAC compensates the increasing need of bandwidth to counter the growing load. As there will be sufficient bandwidth for nodes to transmit their packets, Queue-MAC has low packet loss ratio, thus Queue-MAC keeps performing on the optimal energy consuming state.

Other experiments have also been conducted, with either synchronized periodic traffic generation (burst at the beginning of each superframe) or periodic traffic generation with offset. Similar results are observed but not presented in this paper due to the space limit.

5.2. Comparison with IEEE 802.15.4

5.2.1. Implementation

To validate the feasibility that Queue-MAC can be implemented in existing standard and can have an outperforming effect, we compared Queue-MAC with an optimized IEEE.802.15.4 MAC.

We assumed that every packet in the experiment is time critical so all packets have the same priority to be sent out. In the IEEE standard, sensor node will send control packets to cluster head or router in advance for GTS allocation for time critical packets. While in our implementation, to keep consistency in the comparison and also to show the performance of Queue-MAC in a fair way, we made kind of optimization into the IEEE standard. We assumed that the GTS allocation requests are piggybacked onto data packets like Queue-MAC, no specific control packets needs to be sent in advance.

With the same test bed, we set up a single cluster network, which contains one sink, one cluster head and up to 30 nodes. By altering the number of nodes, we

varied the network load. The maximum forwarding queue capacity is set to be 50 in each node.

For the consistency with the IEEE 802.15.4 standard and also for the convenience of our implement, for both MACs, we set the TDMA slot duration in our experiments to be 4ms, which corresponds to the slot duration 3.84ms in IEEE 802.15.4 standard with parameter Superframe Order (SO) set to be 2, and we set the superframe duration to be 491.52ms to meet the IEEE standard superframe duration with parameter Beacon Order (BO) set to be 5, and only maximum 7 GTS slots are permitted to be allocated in the IEEE standard. Here we set the MAC packet length to be 95 bytes (it is 120 bytes in section 5.1) considering the short time slot duration. Also, un-slotted CSMA scheme is used instead of slotted CSMA. The GTS slots allocation strategy of IEEE 802.15.4 MAC resembles to Queue-MAC, the threshold T_1 is set to be 1, and T_2 to be 2. For Queue-MAC, we set the CSMA period to be 40ms, and no bound for the TDMA slots allocation. Each experimental scenario last for 40 seconds and was conducted ten times, and we took the mean value of all data.

5.2.2. Experimental results and analysis

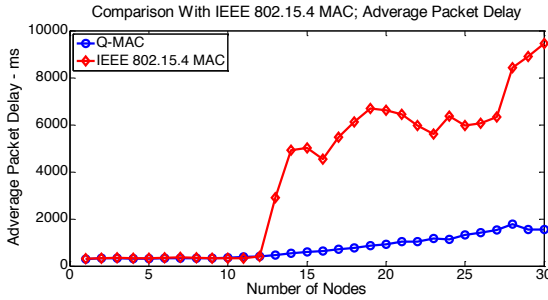


Figure 11. Average delay of Queue-MAC and IEEE 802.15.4 MAC

Figure 11 shows the average delay of the two MACs. When the network is under small scale (number of nodes < 13), both MACs have surpassing bandwidth to deal with the load thus the delay is small. The delay of IEEE 802.15.4 MAC starts to significantly increase after the nodes number goes beyond 13 and this is mainly due to the limited bandwidth as only 16 slots are permitted in the standard. Packets get buffered in the forwarding queue for much longer time than that in Queue-MAC. The delay of IEEE 802.15.4 MAC could be at most 8 times bigger than Queue-MAC (number of nodes = 14). Due to adaptively TDMA slots allocation, delay of Queue-MAC just increases slightly as traffic load grows.

Figure 12 is complementary to Figure 11, it shows the maximum delay the packet could experience during each scenario. The maximum delay of the IEEE standard can be at most 8 times (number of nodes = 14) as that in Queue-MAC. Overflow occurs in those nodes having

packet delay larger than 25 seconds as new generating packets are dropped. We can see a similar result that Queue-MAC has an outstanding performance.

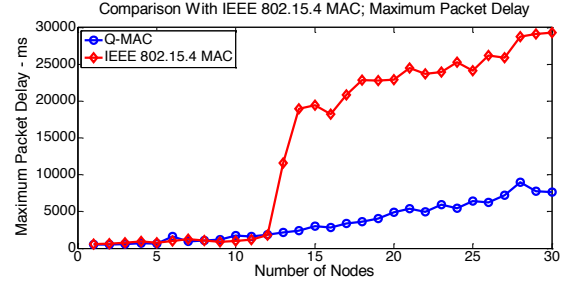


Figure 12. Maximum delay of Queue-MAC and IEEE 802.15.4 MAC

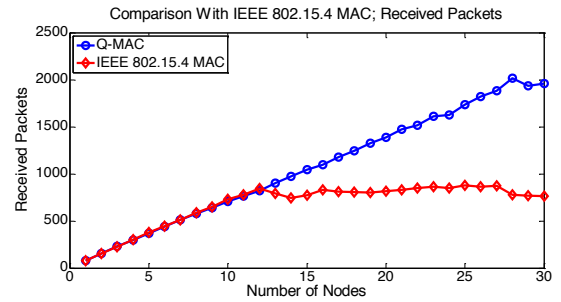


Figure 13. Received packets per scenario of Queue-MAC and IEEE 802.15.4 MAC

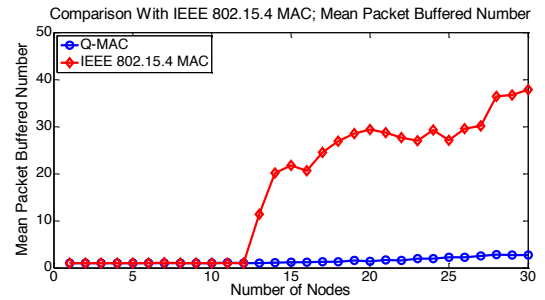


Figure 14. Mean buffered number of Queue-MAC and IEEE 802.15.4 MAC

Figure 13 shows the received packets number per scenario and Figure 14 shows the mean buffered number of nodes at the end of each experimental scenario. When the number of nodes grows beyond 12 in both two figures, throughput of IEEE 802.15.4 MAC starts to be bounded and packets start to be buffered in the forwarding queue. The bad performance is due to the limited bandwidth that IEEE 802.15.4 MAC suffers from the fixed 16 slots active length. On the contrary, the throughput of Queue-MAC has linear relationship with the number of nodes and achieves high throughput at the end. The throughput of Queue-MAC can be 2.5 times (number of nodes = 30) as that of the IEEE 802.15.4 MAC, and it could be even bigger due to the bandwidth adaptability of Queue-MAC. With dynamic TDMA

period to counter the load, few packets are buffered in the forwarding queue in Queue-MAC which leads to better performance on packet delay and throughput.

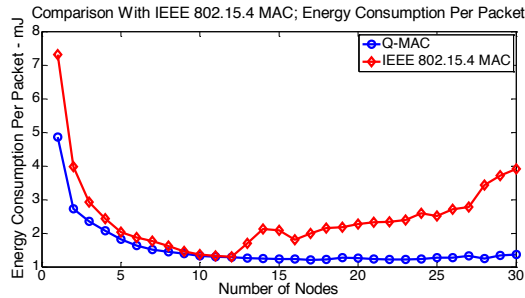


Figure 15. Cluster head energy efficiency of Queue-MAC and IEEE 802.15.4 MAC

We can observe a similar result in Figure 15 that Queue-MAC outperforms IEEE 802.15.4 MAC in energy efficiency. For the same reasons analyzed in 5.1.2, fixed duty-cycle of the IEEE MAC has idle listening and queue overflow issues which lead to energy inefficiency. With the adaptable bandwidth, Queue-MAC keeps its high energy efficiency in nearly all scenarios.

6. CONCLUSION

The aim of this work is to find an efficient low power (so low duty-cycle) MAC protocol, which can also provide high bandwidth for timely dealing with burst traffic triggered by events. Among existing low duty-cycle MAC protocols, seldom can achieve this purpose. This has led us to design Queue-MAC, which is a queue-length aware hybrid CSMA/TDMA MAC protocol. Two main features are embedded into Queue-MAC: the queue length indicator for learning the traffic load and allocating the suitable bandwidth accordingly, and the hybrid CSMA/TDMA medium access control scheme for efficiently dealing with both light traffic and high traffic situations. Queue-MAC protocol has been successfully implemented on STM32W108 SOC chips. Through extensive experimental measurements, we show that Queue-MAC largely outperforms the fixed duty-cycle CSMA MAC and the IEEE 802.15.4 MAC protocols, in terms of throughput, latency and energy consumption. This is achieved thanks to the dynamically adjusted duty-cycle of Queue-MAC. Queue-MAC can be implemented on the IEEE 802.15.4 standard compliant chips, by refining the beacon frame according to the Queue-MAC beacon definition, and by adding queue indicator field at the beginning of the payload of the IEEE 802.15.4 data packet. Our future work aims to further demonstrate the outstanding performance of Queue-MAC by carrying out experimental measurements in a multi-hop cluster-tree network.

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